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REVIEW OF SENSOR TECHNOLOGY AND POTENTIAL IIP APPLICATIONS

Annex M of Cost and Operational Effectiveness Analysis for Selected International Ice Patrol Mission Alternatives

Richard F. Jacob

EER Systems Corporation
Vienna, VA

FINAL REPORT

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G. T. Gunther
Technical Director, Acting
United States Coast Guard
Research & Development Center
1082 Shennecossett Road
Groton, CT 06340-6096

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16. Abstract

This report is Interim Report Volume 13 for the Cost and Operational Effectiveness Analysis for Ice Patrol Mission Analysis Study. The International Ice Patrol uses airborne radar surveillance as the primary detection method for locating, identifying and classifying icebergs. The existing AN/APS-135 SLAR radar is based on a dry film processor technology and is scheduled to be upgraded with a digital processor. The AN/APS-137 FLAR radar is primarily used for identification and classification purposes. This report reviews performance aspects of these systems and presents an analysis of alternative sensor systems and improvements that would enhance iceberg detection, identification, and classification. The technical review covers SLAR and FLAR systems, but focuses primarily on Synthetic Aperture Radar (SAR) systems. Airborne and satellite platforms are considered and suggested radar improvements for future applications are described.

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METRIC CONVERSION FACTORS

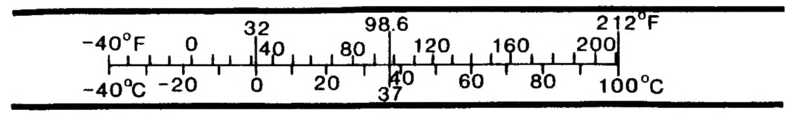
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



REVIEW OF SENSOR TECHNOLOGY AND POTENTIAL IIP APPLICATIONS

ABSTRACT

The International Ice Patrol uses airborne radar surveillance as the primary detection method for locating, identifying and classifying icebergs. The existing AN/APS-135 SLAR radar is based on a dry film processor technology and is scheduled to be upgraded with a digital processor. The AN/APS-137 FLAR radar is primarily used for identification and classification purposes. This report reviews performance aspects of these systems and presents an analysis of alternative sensor systems and improvements that would enhance iceberg detection, identification, and classification. The technical review covers SLAR and FLAR systems, but focuses primarily on Synthetic Aperture Radar (SAR) systems. Airborne and satellite platforms are considered and suggested radar improvements for future applications are described. The technical contact is Dr. Richard F. Jacob, EER Systems Corp., Huntsville, AL.

INTRODUCTION

Objective.

The key aspect of International Ice Patrol operations is the detection, identification, and classification of icebergs. This may be accomplished using various sensors and platforms. The purpose of this report is to review current sensors and other potential platforms and sensors that may have a potential application in the IIP.

Search Operations

As described in greater detail in Reference [1], IIP search operations conducted in HC-130 aircraft operating from St. John's, Newfoundland are the principal source of berg sightings, identification, and sizing to provide inputs to the berg drift and deterioration model, which provides determination of the Limit of All Known Ice (LAKI) and the reports of isolated "radar objects" outside of these limits. These aircraft currently employ one nose mounted Texas Instruments AN/APS 137 FLAR and two Motorola AN/APS 135 SLARS with side-pod mounted antennas.

Four all-day surveillance missions, each providing several thousand square nm coverage, are nominally performed over a two week period by crews temporarily stationed in St. John's. Flight paths are selected to provide coverage from about 50km in advance (east and south) to about 100 km behind the current LAKI. Total coverage of the LAKI in two weeks is provided with almost 100% reliability, although depth of search may be

curtailed at the LAKI greatest extent. Visual search is performed whenever possible, but the vast majority of new target entries are provided by the radars.

Sensor Iceberg Detection

Detection performance for the SLAR, based on test sorties flown under current operating conditions with visually sighted truth data, and supported by independent theoretical performance estimation in Reference [1], is potentially high (99%), but achievement of this rate depends on perfect operator scrutiny of a back-lighted nine-inch strip of real-time developed photographic negative for the presence of images with dimensions from 0.06 to a few tenths of a millimeter in size, against a uniform to mottled (buttermilk) grey background of Bragg scattered sea clutter. This performance has been achieved in performance tests by " alerted " operators, i.e., operators who have been apprised of the presence of bergs, and the general location. Achieved detection performance for unalerted operators (Reference [1]) is on the order of 99% to 30%, with the lower number applying to heavy sea state conditions.

The AN/APS 137 FLAR provides both search and Inverse Synthetic Aperture (ISAR) imaging modes. FLAR detection performance is empirically observed by operators to be inferior to SLAR (some objects found by the SLAR are not found by the FLAR, and/or cannot be locked onto (a process involving developing a reasonable quality electronic track preliminary to ISAR high-resolution imaging) even when detected. Attempts to transfer targets from SLAR to FLAR are essentially impossible, since the FLAR waveforms are the same for the most commonly used search mode and lock-on/imaging. Existing FLAR truth data studies find reasonable (80%) FLAR detection on small bergs and growlers. False alarms are virtually non-existent for the FLAR, since lock-on and track are required before operator entry.

Both radars are assumed to be providing high detection probability for bergs in the "Medium" and "Large" size category. The BERGSEARCH '84 study (Reference [2]) indicates that this is true for the SLAR, even with an unalerted operator. No study has been provided to the team that unequivocally predicts high FLAR detection performance, even for large bergs.

Discrimination of ice from non-moving ships (moving ships are discriminated by the FLAR by the display of velocity components after track is achieved) and ice sizing are strongly dependent on the pattern recognition of trained operators.

The FLAR images of either ships or ice rarely (never during several sorties observed by a study team member) resemble textbook depictions of ISAR images. While textbooks show weak and mildly distorted line drawings from an arbitrary perspective having to do with the principal axes of object periodic rotation, the realized FLAR images take the form of undulating bands of medium to high brightness areas. The possibility that the FLAR is misadjusted, suffers from deliberately crippled imaging capability. or is simply not the most currently available technology (introduced as a possibility in Reference [1])

has been ruled out by knowledgeable USCG personnel, who have personally observed the performance of this radar on other platforms and under varying operational conditions. Operator pattern recognition can plausibly produce a reasonable probability of ship vs ice discrimination, but controlled studies with rigorous truth data are not conclusive or numerically adequate on this issue.

SLAR discrimination is claimed and was observed by the team in some cases, but discrimination is assumed by the IIP to be principally provided by the FLAR.

On the rare occasions that visual observation is possible, sizing can be reliably performed. Sizing clues are provided by both radars, but are subject to operator interpretation. Sizing performance has not been adequately documented. The deficiency is recognized, and is partially compensated by the conservative strategies of setting the initial size of a berg entered into the data base at the upper end of the size range for the estimated size category, and providing for object retention as a possible establisher of the LAKI until "150% melt" has occurred. The inadequacy of these strategies when original misestimates are more than one category are noted in Reference [1].

SEARCH EFFECTIVENESS/CURRENT SYSTEM CONTEXT

The current search and propagation procedures provide a LAKI estimate that is conservative in the sense that there is a tendency for objects to be carried longer than is believed necessary. The advantage of this procedure is that the published LAKI, compensated for errors in the estimated size, sea temperature, and melting model, is less likely to produce leakers that are a hazard to navigation. Since the search area is also based on a LAKI that is conservative in this particular sense, many of the search sorties find few or no bergs.

Although affordable sensor and data processing improvements, as identified below, can improve the reliability of the detection, identification, and sizing procedures, these should be evaluated for necessity and effectiveness in the context of the current or some improved berg propagation/melting model combination. Improvements in berg drift modeling may, for example, permit narrowing of the current search swath width consistent with present probability of loss of a berg track.

The current berg position estimation between sightings procedure is:

- Enter berg estimated initial position after detection into the drift/melting model. Associate an initial five nm position uncertainty.

- Estimate berg future position from effects of local estimated wind and current, with future positional error compensated by an additional 5 nm per day error up to 30 nm, The LAKI is drawn at the outer limits of the error circles for each propagated berg.

If the nominal search sector is distance Δs leading the LAKI and Δw trailing, a leaker (this terminology is clearly applicable only to objects that remain intact) sufficiently beyond the LAKI to be more or less permanently lost (dependent on the accidental future proximity of an unlost object to be recovered) is thus caused principally (the list is not exhaustive, but covers the principal causes) by one of the following:

(1) An object never detected and lost because the (uncompensated) motion during a two-week interval exceeds Δs + the distance by which the object trails the LAKI at the time at which the object would have been detected if detection had occurred (and/or Δw had been sufficiently large) + the distance moved by the LAKI in the direction of object motion during the two-week interval. The combination of object initial size and ambient melting conditions must also be conducive to survival of the object for a two week interval for the leakage to occur.

(2) Detected for one or more contiguous intervals, never missed, but lost because the positional error (after nominal motion compensation) normal to the LAKI after a two week propagation is greater than 30nm (N of 40 degrees North; 55 nm South of this line) plus Δs plus the distance by which the object trails the LAKI at the time of last detection. The combination of object initial size and ambient melting conditions must also be conducive to survival of the object for a two week interval for the leakage to occur.

(3) Detected for one or more contiguous intervals, missed during the interval preceding loss, and with a four week (compensated) error greater than 30nm + Δs + the distance by which the object trails the LAKI at the time of last detection + the four week motion of the LAKI in the direction of the object motion. The combination of object initial size and ambient melting conditions must also be conducive to survival of the object for a two week interval for the leakage to occur.

(4) Premature deletion of an object detected at time delta t succeeding the last detection, accompanied by an (uncompensated) motion of more than Δs + the distance by which the object trailed the LAKI at last detection + the LAKI two-week motion in the direction of object motion.

Temporary misplacement of the LAKI may also occur when a detection miss occurs, but the motion error conditions of (3) fall short of being satisfied by less than Δs, provided the object is subsequently redetected. Leakage, and concomitant trailing mislocation of the LAKI, is caused, with high probability, by one of the above situations. Thus:

- Although growlers are known to be the principal obstacle to navigation because of the detectability of larger bergs by ship radars, they need be detected only when they will survive long enough to become leakers under one of the above conditions. Reliable search at high resolution well within the LAKI is thus not required in warm water. Operation of the SLARs on either side of the aircraft at different swath widths should therefore not be ruled out.

- All of the above conditions are less likely if local drift conditions are specified in the model with as much precision as possible. In regions of high variability (divergence or curl of the drift vector field) of the historic current database, the nominal daily drift error should be increased.

- The available test data on the drift model implies, however (Reference [1]) that errors as large as the assumed daily error may occur even in the presence of perfect knowledge of the prevailing currents and wind, so that reduction of the propagation interval is highly desirable.

LAKI overmotion may be caused by the current conservative corrections, or by false alarms (rare with the current sensors) or identification errors (not uncommon with the current sensors), but are, in the case of identification of a ship as a berg, at least corrected at the next search opportunity.

SYSTEM UPGRADE OPTIONS: SENSOR-RELATED INFORMATION HANDLING AND DATA PROCESSING.

Sensor and overall system effectiveness may be both quantified and improved if modern data processing and information handling techniques are applied in every stage of the IIP operations, from data gathering to flight path planning. Moreover, although the current procedures are conscientiously and professionally applied, the achieved effectiveness is only qualitatively understood.

Each of the upgrade options below is capable of making a worthwhile improvement in sensor performance with the current system, or a modification thereof.

SLAR Digitization.

The AN/APS 135 SLAR is capable of providing detection with high reliability, and can be part of a high-confidence system, but is subject to detection failures due to operator inattention. Pickoff of the CRT intensity modulation signal, analog-digital conversion, and image processing by a standard PC to provide an operator alert and display, on a subsegment of the current film swath, an image that preserves the achievable radar resolution with an encircling icon is a practical modification that can permit human pattern recognition to be applied to the final designation process for target selection.

This modification, combined with a common GPS navigation system for the SLAR and FLAR would provide the possibility of error-free merger of radar objects. Provision for display of previously recorded images simultaneously with new, second-look images would make correlations obtained in the 200% coverage error-free, and aid in sizing and ship discrimination.

Data recording requirements to permit SLAR unmanned operation by storage of single pixel data are easily within PC hard disc drive capability, as shown in Figure 1. For either modified or current SLAR, calibration based on several permanent surface targets of known radar cross section, placed along or near a portion of the route from St. John's would permit assurance of operator adjustment of SLAR bias and gain to obtain optimum usage of radar dynamic range, and provide, in current film form, or, for the digitization option, in digital form compatible with CD ROM, an unsurpassable data base for future validation of clutter models.

Automated Flight Path Planning.

In principle, significant improvement (5dB - Reference [1]) in the realizable signal to clutter ratio for current sensors or any future options may be obtained by orienting flight paths to provide crosswind aspects perpendicular to the flight path (i.e., orientation of aircraft motion parallel to surface wind speed) for the SLAR. In practice, this requires preflight knowledge of surface winds, which is not reliable. A preliminary route based on surface wind predictions, supplemented by one or more complete alternative paths, with the selection based on readings obtained in the operational environment from a previously calibrated SLAR is, however, a viable technique for sensor performance improvement which applies to SARs as well.

Function	Requirement
Flight length	1.00E+3 nm
Ground/chart length at 500000 scale	1.80E-01 in/nm
Total chart length	1.80E+02 in
Total area at 9.0 in width	16.2E+03 sq in
CRT spot size	3.0E-2 mm
Total pixels for 1000 nm	1.16E+09
Total memory for 1000 nm @ 2 bytes/pixel	2.32E+09 bytes
Required Storage rate at 250 nmh	1.6E+05 bytes/sec

Figure 1. Data Recording/Throughput Requirements for SLAR Upgrade

Search Effectiveness Determination.

Visual sightings of bergs by surface vessels are routinely entered into the drift/melt model on a daily basis. These objects can provide a continuous source of truth data for ongoing evaluation and sensor search, identification, and sizing effectiveness, since most or all are sighted within or just outside of the LAKI. Comparison of search sortie results with new visual sightings sufficiently fresh to permit unequivocal positional correlation is clearly viable, and can be the basis for chi squared tests to provide confidence levels for current effectiveness parameters, or of the utility and reliability of system operational modifications.

SENSOR REPLACEMENT OPTIONS

SLAR/FLAR Upgrade.

The existing AN/APS 135 SLAR, upgraded as described above, will be increasingly difficult to maintain and obtain parts for. Any SLAR system providing similar coverage on a similar scale will, however, still be subject to missed objects, and must also be wedded in some manner to another system capable of achieving positive identification of ships and target sizing.

It is our understanding that an improved TI FLAR (perhaps not yet available) exists that incorporates an ISAR imaging mode that indeed obtains relatively undistorted ship images under all or most rather than some conditions. Assuming this is the case, a reliable iceberg image, permitting accurate sizing, is still probably not obtainable, for the following reasons:

- The development of a stable ISAR image depends on measurement of the object motion over an interval of several seconds to determine the angular velocities of the rotational motion about two axes.

- The forced (by wave action or otherwise) rotational motion of a rigid body having three distinct moments of inertia is inherently stable (and thus permits development of signal processing to prevent periodic flip-flop of the Doppler derived image) only about the axes corresponding to the maximum and minimum moments of inertia. Forced motion tending to produce an oscillation about the axis corresponding to the intermediate moment of inertia will not persist, or simply decay, but is (in the impulse excited case) transformed fairly rapidly into motion about both of the other two axes.

- Marine architects are aware of this fact, and will provide the maximum moment of inertia about the most readily excitable (during forward motion) pitch axis, while the roll axis corresponds to minimum I. A ship at rest (the only case where the image is necessary to provide identification) may be a relatively poor ISAR target, since yaw motion may be excited.

- Since a berg has no significant translational motion, rotation around either of the two larger moment of inertia axes is equally probable, and will be degenerative in the sense described for one of these axes. Bobbing motion will also be exaggerated for any berg, and complicates motion filter construction.

Synthetic Aperture Radar (SAR).

Synthetic aperture radars are capable of producing high resolution images over large areas rapidly, and are thus, in principle, ideally suited to the IIP mission. In general, SARs employ high range resolution waveforms (chirped or stepped frequency) to obtain range resolution that is similar to the angular resolution along the flight path that is

obtainable from the synthetic aperture processing. For an (optimally compensated) focused SAR, the minimum cross range resolution is independent of range, and is, for an optimal design, 0.5*(system real aperture). All SARs are subject to speckle noise, for which the signal-to-noise ratio following N incoherent looks is $N^{1/2}$, regardless of how many pulses have been integrated during the time of traversal of the SAR aperture. Synthetic aperture radars may be operated in either scanning (typically side-looking) or spotlight mode; in the spotlight mode, the antenna must be physically or electronically rotated to focus on the same area as the platform moves.

Synthetic apertures for iceberg detection may employ satellite, manned aircraft, or drone platforms. Advantages/ disadvantages of each of these options are discussed below.

Satellite Borne.

The principal advantage of satellite vehicles for the IIP mission is that large areas are covered at relatively low recurring cost, and that performance of search, per se, is not vulnerable to weather constraints. Since avoidance of range ambiguities restricts the maximum unambiguous range swath of SARs to $R_u < cD/8v$, here D is the antenna extent along the track and v the velocity of the platform, and, as noted above, the minimum cross range resolution $\Delta r_c = D/2$, so that the maximum number of slant range (square) cells is about 10^4 (i.e., 100 km at 10m; the signal-to-noise ratio requirements are already difficult to meet at this cell size), so that 25-50 meter resolution is typical. Within current technology constraints, raw data must be downlinked to multiple receiving sites for processing. The synthetic aperture achieved by satellites is large, but the ratio of synthetic aperture size to range to target is similar for satellites and airborne platforms. Satellites are also superior to airborne platforms in that depth of focus constraints (see Airborne SAR) are more easily satisfied at arbitrary incidence angles.

Early satellites (e.g., SEASAT, ERS-1) represented a specific point design resolution of a three-way tradeoff between swath width, resolution, and radiometric accuracy. The RADARSAT Canadian satellite, currently anticipated for launch late in 1995 and operational capability in 1996, employs parameter diversity consistent with multiple optimum designs. For IIP short term consideration, data available from RADARSAT represents the definitive satellite option.

RADARSAT is to be deployed in a sun-synchronous, nearly polar orbit, and permits several different swath width/resolution options . In the wide swath mode, coverage of the entire region of interest to the IIP is achievable in a single pass (Not all orbits are correctly positioned to achieve single-pass total coverage, however.) Positional accuracy is approximately 1km. A revisit cycle of approximately four days is practical at the wide swath resolution of 100m. This will detect large bergs, and is thus potentially useful for as an augmentation of current or revised IIP search. The data will be for sale through a private company that has been employed as a "value-added" distributor at approximately $1000 per (500 km square) image.

C-band is employed for the RADARSAT carrier, which places the backscatter coefficient for ice between the maximum and minimum possibilities for sea clutter backscatter coefficient as a function of incidence angle and sea state. If high clutter rejection is not achieved by the signal processing (Not true for STAR1, which also employs chirped pulses, as noted below. The number of independent pulses integrated by the systems is similar.), the system will thus have unreliable detection capability for bergs, even in the narrow swath mode. In the wide swath mode, RADARSAT is obtaining only four looks at some ranges, for a speckle signal-to-noise ratio of 2, with a concomitant high false alarm rate for single pixel bergs (sea clutter and ice returns will also have standard deviations reduced only to 1.414*average; see discussion below for airborne SAR). The false alarm rate is of concern precisely to the extent that false alarms ever become the basis for adjustment of the search region. If RADARSAT data is used to provide supplemental detections of large bergs (4 pixels or more) in unsearched areas only, the likelihood of false alarm is significantly reduced. Detection of large bergs is also readily accomplished by the Groundwave Radar, or by the widest swath SLAR mode.

Airborne SAR.

Airborne SARs are a viable alternative to the current sensor suite and platform for the IIP mission. In the BERGSEARCH '84 study, the STAR1 SAR was found superior in detection performance to four other systems tested under similar operational conditions with truth targets. (It is not clear that the AN/APS-135 performance did not suffer from inadequately trained operators in this test, as noted in Reference [1]). Both STAR1 and its successor STAR2 offer rapid coverage of large areas using small commercial jet platforms. The improved STAR2, for example, carries two radars to provide a 63 km swath width at 7m cross-range resolution at 400 knots for five hours, permitting coverage of the entire typical two-week mission in two days or less.

Although tests measured operational performance for subjective operator discrimination of ice, the P_{det} and P_{fa} parameters explicit to small (one-two pixel size) bergs with a heuristically optimized grey scale threshold was also attempted in the BERGSEARCH '84 document, as described below.

These and other commercially available multi-purpose airborne SARs are compromises not currently optimized for IIP requirements, however (modification to correct problems and improve observed performance significantly may be possible). A principal tradeoff for such systems is range focusing depth , ΔR_f vs. resolution, Δr_c, which must satisfy the relation

$$\Delta R_f = 8(Dr_c)^2/\text{lambda}$$

(for a quarter wave acceptable quadratic phase error across swath) so that, e.g., at 10 Ghz, for a desired 6m crossrange resolution, 9.6 km of focus depth is available. The ground range obtainable from this depth at an altitude of 10km is 16.9km if the inner edge of the swath is at near vertical incidence, but only 12.8km if the angle of incidence for the

swath inner boundary is at an incidence angle of 30 degrees. In the SARs examined in BERGSEARCH '84 (STAR1 and CCRS CV-580), small inner boundary incidence angles (8° and 2°, respectively) are accepted to optimize swath width. This creates two problems for the IIP application:

- The backscatter coefficient, σ_0, is actually much larger for ocean than for level ice at the inner boundary (see Figures 2 and 3), so that, even after some reduction in sea return due to motion, the signal to clutter ratio is undesirably low.

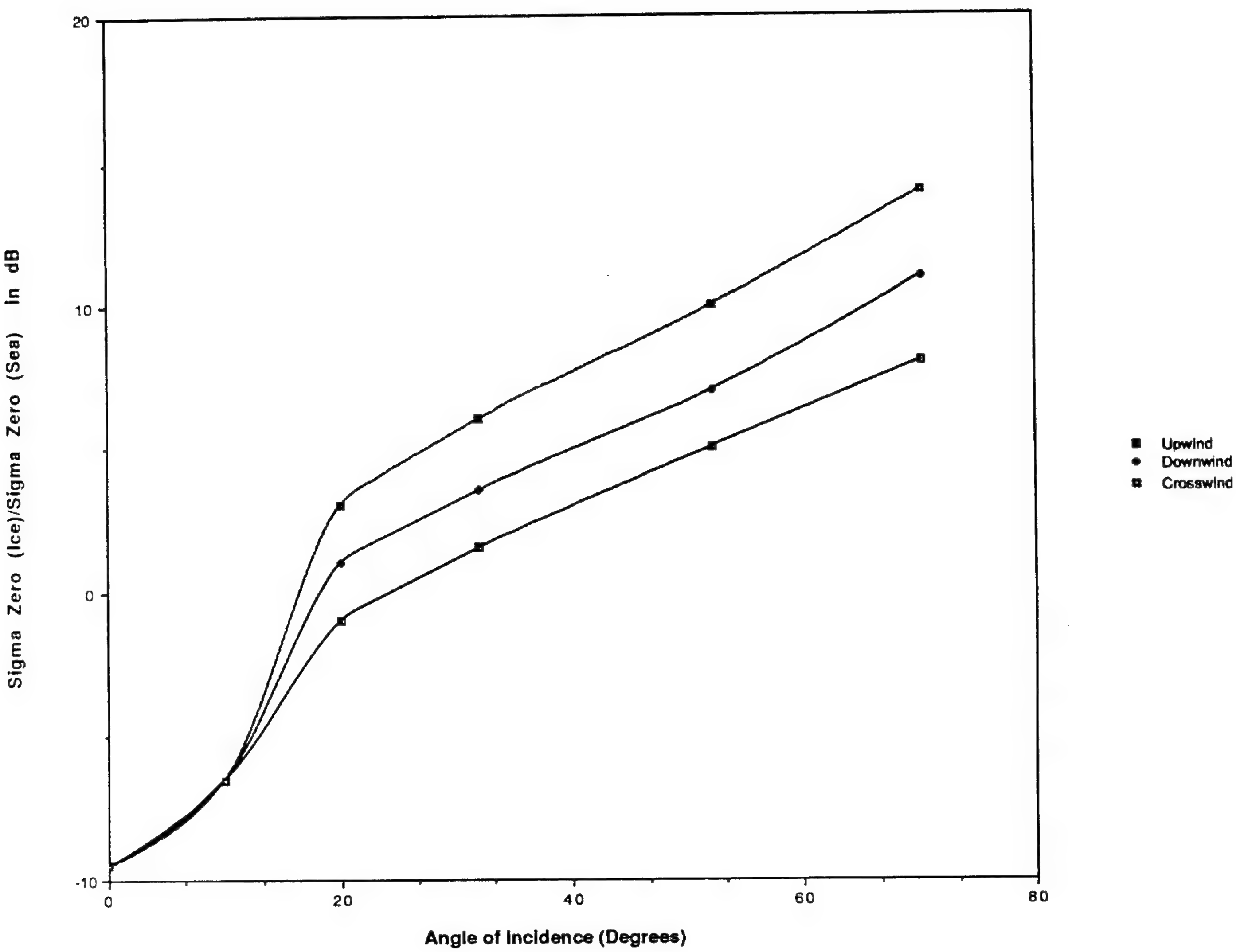


Figure 2. Backscatter Ratio (Ice/Sea) at X-band HH for Wind Velocity 14.5 m/sec.

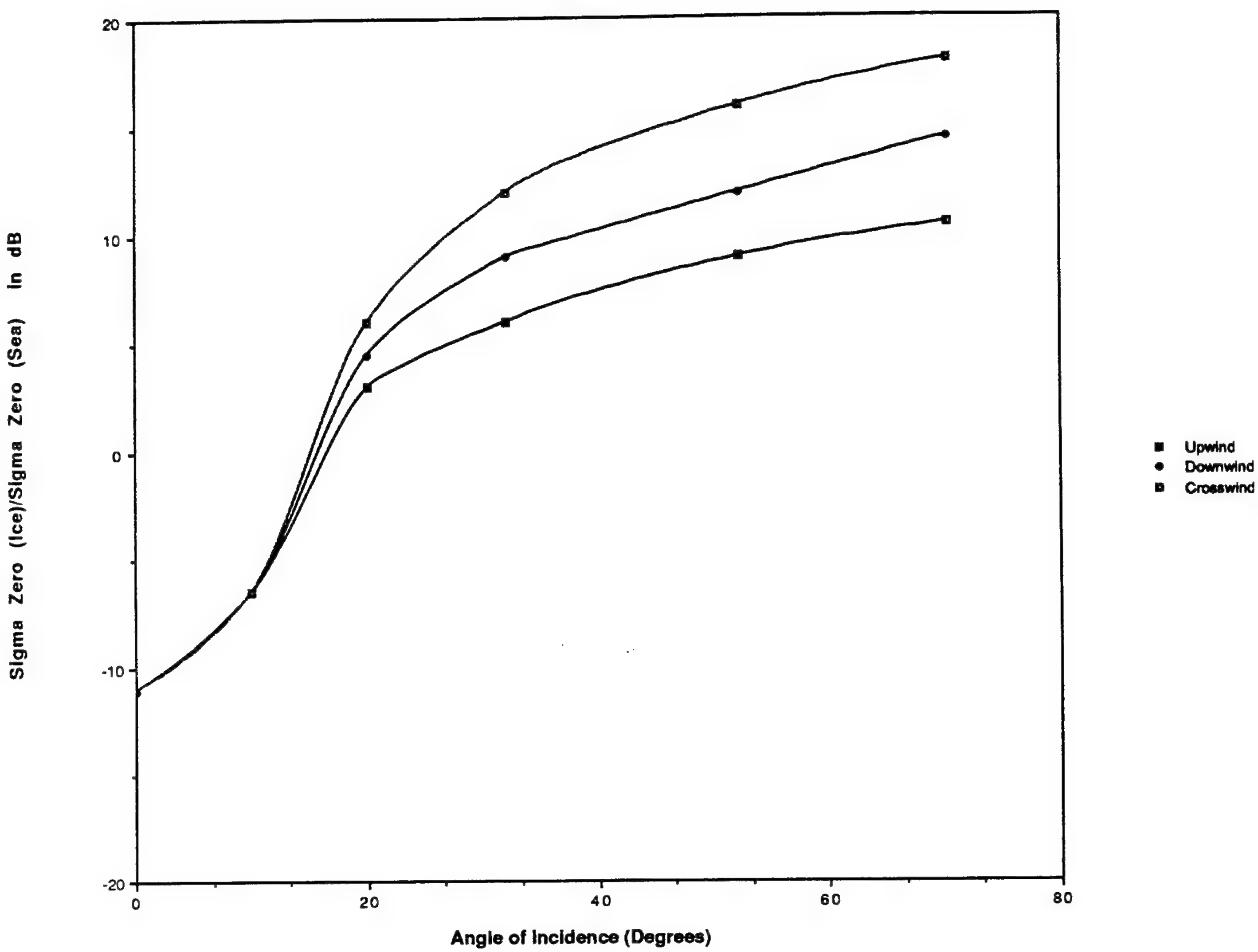


Figure 3. Backscatter Ratio (Ice/Sea) at X-band HH for Wind Velocity 9.3 m/sec.

- The slant range resolution, Δr, is constant across the swath, the ground range resolution is varying as 1/(sin(angle of incidence from normal), and, if Δr is 3m (6m is reported in Reference [3] for STAR1, but may be mean ground range resolution), the ground range cell length is varying from 21 meters at the inner edge to 4.2 meters at the outer edge for STAR1, so that the ground range resolution, and the width of the clutter/target cell from which signals are being integrated, are varying strongly across the swath. Uniformly sized cells are displayed (see BERGSEARCH '84 Appendix), suggesting that single SAR cells are subdivided into multiple screen cells at some angles.

Moreover, although some berg and sea return cells are easy to classify, a grey scale threshold optimized for high probability of ice detection at an acceptable, low false alarm

rate is highly desirable for IIP application if improvement to a validated system is to be achieved, and probably not built into any available system.

The anticipated probability of detection/false alarm tradeoff for a global average of conditions, specific sea state, is given for STAR1 (used in the BERGSEARCH '84 study, as computed empirically by the study team) in Figure 4. This curve was derived by measuring the pixel grey scale distribution for a particular day of the study, for which passes were made in various geometries relative to wind direction. Targets selected for this distribution were on the order of one-two pixels in size, and approximately randomly distributed across the search swath. (Unfortunately, the data has not been corrected for the fact that the processor is applying an apparent non-uniform gain, probably corresponding to the reciprocal of average pixel return at a given offset, and what seems to be, in Figure 5, a non-zero origin for the distributions.)

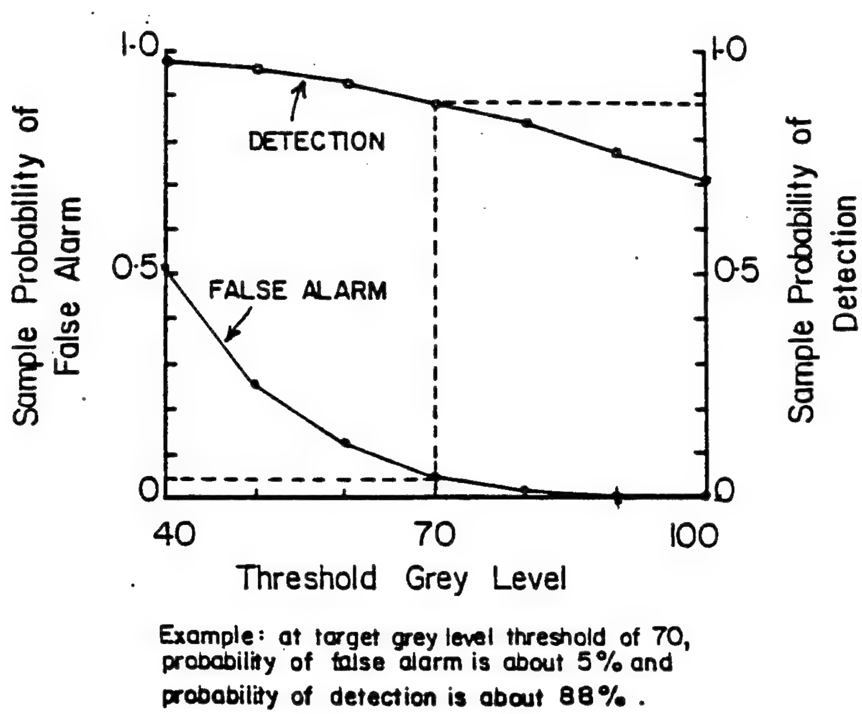


Figure 4. Empirical Pdet, Pfa from BERGSEARCH Appendix--STAR1 SAR.

The variation which appears in the distributions in this document includes both the variation in the returns from a single patch of ocean or ice which occur as a result of phase summation, which is nominally Rayleigh distributed for a single pulse, and the distribution over incidence aspect and surface/volume conditions. The latter is a theoretically unknown distribution; the combination of the two is probably well approximated by this data. It is assumed herein, though not stated in the appendix, that the range of incidence angles for each " Ocean " sample is small, but may vary from sample to sample.

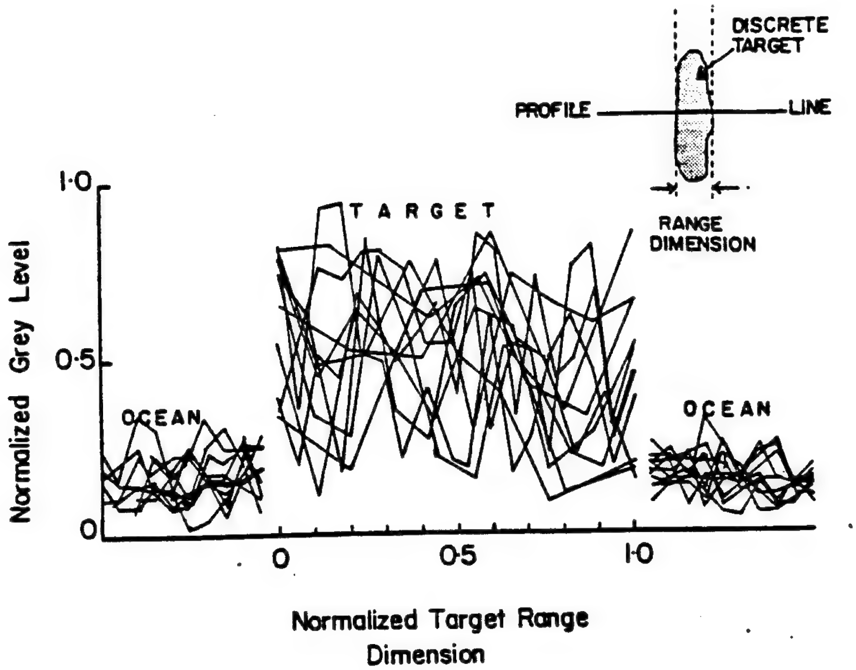


Figure 5. Raw Data from BERGSEARCH Appendix for Grey Scale Distribution Across Center of Large Bergs vs, Sea Clutter Distribution on Either Side--STAR1 SAR.

An important aspect of the BERGSEARCH appendix data is that there is little mean sigma zero difference for "Target" vs. "Ocean" average grey scale readings (quantitative estimation is difficult, since the origin probably does not correspond to zero return the margin seems to be between three and five dB). This is not surprising, since the average backscatter coefficient ratio (ice/sea) over the 8° to 35° incidence angle range for STAR1 is approximately one (See Figures 2 and 3; the ratio plotted in these figures is directly relevant to single-cell berg return at small off-normal incidence angles only if the bergs present a horizontal surface extending for at least one or more cells). For berg segments presenting principally vertical or steeply sloping surfaces at small sea surface aspects the total cell return will be down significantly from the values of Figures 2 and 3 for the vertical return cells since both σ_0 and the cell surface area sampled by one pulse are reduced at small incidence angles (to the normal). Moreover, any grey scale gain factors to accommodate cell size changes will be ineffectual and possibly counterproductive. Reduction of sea clutter vs. berg return is not provided by the frequency diversity present in a chirped pulse, since, if the carrier center frequency does not change with frequency, the pulse returns are not independent. Motion is, however, sufficient to provide substantial decorrelation for both sea and ice. Although the platform motion is compensated for in signal processing, Doppler due to wave and ice motion in both horizontal and vertical directions is not. At a typical wind velocity of 9m/sec, the wave crests have velocities nearly the same as the wind velocity, and will produce phase shifts between consecutive pulses at a frequency of about 600Hz for upwind and downwind looks, corresponding to a pulse-to-pulse phase shift of nearly two radians between pulses. Ice translational motion is much smaller (.07m/sec sustained at 5nm/day,

still sufficient to produce a few hundredths of a radian pulse-to-pulse); in upwind or downwind geometries, where signal to clutter ratios are most unfavorable, a pre-integration lowpass recursive digital filter can be used on the single cell complex returns to provide significant gain increases for ice. This processing mode is apparently not a feature of the STAR1 SAR, which exhibits only about 3-5 dB suppression of sea clutter at near-vertical incidence, as noted below.

To the extent that sea backscatter is due to Bragg scattering (multiple returns from crests and troughs interfering constructively), the Doppler is independent of wind direction and velocity, as discussed in Reference [10].

Note that Figure 4. is applicable only for a single berg, well-centered within a pixel, and is very pessimistic for multi-pixel bergs. It is, however, overly optimistic to assume that adjacent cells on a given berg yield uncorrelated returns from the distribution that gives rise to Figure 4, since adjacent cells are subject to the same, or similar, aspect, roughness, surface spatial correlation characteristics, and underlying bubble size and density. Nevertheless, Figure 4. yields, for a two-pixel berg, and three-pixel berg, under the decorrelated returns assumption, a P_{det} of nearly 99% and 99.9%, respectively, since exceeding the threshold in any pixel is a basis for inclusion. This is a higher false alarm rate than is being obtained by the current sensors, but represents a higher detection rate as well. (For a two or three pixel berg for which ambient surface conditions, volume conditions, and aspect yield a P_{det} below the average for the assumed threshold, say 60%, the P_{det} for the two-pixel berg is still 84%, so that the multiple pixel case is a significantly easier target. The false alarm rate of 5% or so is probably intractable with constant thresholding, since incoherent looks with distinctly different aspects require greater correlation confidence than is currently possible.

The indicated underlying distribution upon which Figure 4. is based has a standard deviation for both sea and ice returns which is nearly equal to the average return (Figure 5; this does not represent a Rayleigh distribution, however, but a combination of the post-incoherent integration Rayleigh and a uniformly averaged-over aspect, vertical viewing angle, and shape distribution.) A superior treatment might be possible by extracting multiple distributions as a function of sea incidence angle (slant range), permitting variable thresholding across the swath. (It is not clear that this is being done by STAR1 or STAR2; what is being done for the display is multiplication by the inverse of the average return at the offset, so that the variation of sea return with incidence angle is not apparent - see Figure 5.)

If cell size inequality is avoided or reduced by excluding near vertical incidence, the probability of sizing error of more than, for example, 25% is clearly minimal, even with the performance of Figure 3. (The probability of interpreting a two-pixel berg as one-pixel is less than .20, and other major miss-sizings are negligible.), suggesting that current sizing safety factors could easily be reduced.

As noted above, STAR2 would make possible coverage of search region of the current typical size (about 500nmi long by 200km wide) in one day (at the wide swath, 25m pixel size, or one-half this coverage at 15m pixel size; incidence angles for this system have not been determined, but may be similar to STAR1), permitting substantial fuel savings for a single sortie, so that the current two week search cycle could be reduced to one week or less at similar operational costs, thereby alleviating the capital costs substantially. A concomitant reduced total searched swath at similar or improved reliability to the current operational mode would become possible because of reduced dependence on drift and melt models. This possibility of more frequent search at similar or reduced recurring cost, described in detail for drone operation below, is the most obvious method of achieving greater reliability with current technology.

Unmanned Aerial Vehicle or Drone as SAR Platform.

The Medium Altitude Endurance (MAE) unmanned aerial vehicle (UAV), currently under development by the U.S. Army and scheduled for availability in mid-1996, is a prop-driven drone which can be equipped with either EO/IR or SAR sensors. The advertised mission endurance capability for this platform is a 500nmi operational radius with 24 hours of continuous coverage at this range. An altitude range of 3000 to 25000 ft. and payload capacity of 450 pounds (It is not clear whether this includes, or is in addition to, the sensor package.).

Complete specifications of the SAR for this UAV are classified, and have not yet proven obtainable. However, assuming an operational speed of 125 knots is possible near the altitude ceiling of 8km, there are no fundamental obstacles to prevent operating at pixel sizes as small as 5.0m x 5.0m, while still providing 7 looks or more. (Assuming a maximum of .7 sec integration time for a single look is possible). A pair of side-looking antennas (this configuration is available for STAR2), each illuminating a 8 km swath to either side of the drone (with an seven km spacing between inner edges, providing incidence angles of 26°-55°) would be necessary to obtain this coverage while avoiding near-vertical incidence angles and providing adequate range focus depth. At the 26 degree inner boundary of the search sector defined above, horizontal ice return for full cells is about 4dB above clutter for the worst case azimuth (search upwind) at wind velocities of 9.3m/sec (see Figure 3), and zero dB above upwind clutter at 14.5m/sec, so that, even at 14.5m/sec, ice is about 3-5dB above sea clutter for normal aspects.

The MAE UAV's advertised capability of 24 hours on station at a 500nmi range from base would thus permit, for example, (assuming a 120 knot velocity is possible at this altitude) a 675nmi (allowing 1/2 hour each for three turns) by 57km wide swath (with 7 km total overlap between the 8 alternating, 8km swaths) to be examined in a single sortie at very high reliability under most weather conditions. If the search is performed in four long segments parallel to the LAKI from front to back, not every berg will be covered by the search because bergs that were originally, e.g., eight km behind the LAKI may drift forward by more than the 1/2 km overlap during the time interval from one swath circuit to another. If the search is back to front, a leaker is produced only when the *differential*

drift between such bergs and those directly opposite on the forward edge is more than 8km in two days. (A miss on large bergs could be avoided by merging RADARSAT data. Note that the frequency of the proposed update makes correlation of berg sightings much more reliable, and thus measurement of actual experienced drift velocity and, thereby, gathering of data to greatly strengthen current drift models.) Such a sortie, repeated on a two day cycle (alternating up and down days) would permit abandoning the current drift and melt models entirely by propagating the leading edge of the search boundary forward using the leading edge of a (conservative) 14nmi per day "maximum" drift circle. (Evidence from Reference [1] indicates that an error this large occurred for one of the bergs in the controlled test of the drift model; allowance for historical currents might make this limit high-confidence, but this is not certain.). Leakage under any of the conditions listed above would be a very low probability event, since the uncertainties of the 14-day propagation interval would not be present. This mode of operation is expected to be economically feasible for the drone (see below).

The principal source of risk in this mode is that a high confidence two-day drift margin is significantly larger than the maximum experienced in the limited truth data, even after correction for historical *and* ambient measured data are taken into account.

Although real-time image production is not required for the drone platform, data throughput requirements on the order of 10 Mbytes per second (see Reference [8]) imply that on the order of 2 million Gigabytes would be required to store the raw data for the 24 hour collection interval. If processing is done in real time, approximately 700 MFlops of computing power are necessary; the resulting data storage requirements are reduced by about 2×10^4 if every pixel is kept, but much more if only pixels above detection threshold are retained, so that the task is manageable. Although the problem is readily pipelined, the processing aspect is formidable; an array processor providing at least 20 nodes of i860 or TMS320C80 equivalent processors would be required. It is not certain that the MAE UAV is so equipped.

Substantial fuel cost savings could be achieved by drone utilization in the manner described above. The current 4 HC-130 single sorties are requiring approximately 8000 gallons of fuel each (Reference [3]), compared to an estimated 1650 gallons for two weeks of UAV operation in the 2 day cycle mode, including fuel to reach the 500 nm range and 24 hours on station, based on a 7 gallon/hour fuel consumption rate for the drone. Aviation fuel is about twice as expensive for the drone, so that a fuel cost of perhaps one/tenth of that for the current operation is expected. (These apparent savings may be reversed by labor cost increases if pilot union regulations require full staffing for the 157 hours of drone flight over the two week period, as estimated for Connecticut. It is not clear that similar restrictions apply to operation in both St. John's and New Jersey. A search for alternate airfields, including other countries, that are in other respects inconvenient, but avoid the union restrictions on drone flight might be plausibly pursued.)

Capital costs for drone operation startup would be significant, but could be amortized over several years. IIP personnel would be responsible for drone flight path

planning and data integration, as in the current scheme, but would have reduced travel requirements to St. John's.

After a year or more of truth data gathering as described above, possibly supplemented by additional flights beyond the LAKI leading edge, sufficient (in a rigorous statistical sense) data could be built up to permit listing of individual sightings within this region, under favorable seasonal conditions, on a three-day basis. Navigation by surface vessels within this search region, while avoiding the expanding error circles of each sighted berg, could thus become a high-confidence surface vessel navigation strategy in many cases, but would rarely result in substantial cost savings. Additional supplementary sorties capable of removing hundreds kilometers could, however, be planned and executed based on cumulative data on leakers to rear of the drone-searched swath, ambient sea temperature, and supplemented by satellite data are favorable, and the rear portion of the searched region has a low berg density.

It should be noted that the MAE UAV is HC-130 transportable, and is being equipped with deicing capability for wing and control surfaces which would be available in the mid-96 deployable vehicle.

Commercially available drones are roughly one-third the price of the UAV, lack current deicing capability, and are subject to the same problems with union restrictions. Time on station/ payload tradeoffs are expected to have been similarly resolved.

Airborne SAR performance will also be improved by the dovetailing search patterns which avoid steep incidence angles. The precise pattern described above requires only 0.156 g's of (lateral) maneuver capability from the drone, but 1.7 g's from the 400 knot STAR2 platform.

Weather Considerations for Drone Operation.

Maintenance of the LAKI by the reduced coverage, reduced revisit cycle method described above is clearly somewhat vulnerable to periods of non-operation of drones produced by maintenance or periods of extremely bad weather. The two day repair cycle allowed for by the suggested schedule is assumed to be essentially continuously maintainable. Storms producing degraded detection probability due to high clutter, or brief periods of weather too severe for aircraft operation can occur in the current IIP operational mode, and result in periods of relatively greater dependence on the drift model, with concurrent loss of reliability (some leakers are believed possible, but data is inadequate to quantify this assumption). If these routine occurrences are assumed no more likely for drone operation, then recapture the drone high revisit cycle/reduced coverage operational mode described above mode described above would require one or more cycles of expanded coverage with reduced capability for growlers and small bergs, but with resulting effectiveness probably no worse than current methods. The statement is supportable only if drone realizable duty cycle is not significantly worse than the HC-130, an assumption which may well not be valid.

SENSOR TECHNOLOGIES REQUIRING DEVELOPMENT

Radar Systems.

Non-Diffracting Radar.

One of the options considered briefly in the study is a "non-diffracting" beam technology based on a 1987 paper by Durnin (Reference [4]) which is applicable to any field obeying the wave equation, including acoustical excitations. It is shown in the original paper that a cylindrical beam, amplitude modulated perpendicular to its direction of propagation as $J_o(\alpha r)$, where α is a constant and $r = (x^2 + y^2)^{1/2}$ when the direction of propagation is z is non-spreading until a maximum z (if the initial α is chosen to optimize the non-spreading propagation distance) of R^2/l where l is the carrier wavelength and R the radius of the beam. Although such a system (incorporating a lens-like beam modulator) would be free of speckle noise and enjoy a 1/Range^2 signal-to-noise ratio, the maximum propagation distance is compatible with satellite operation (Low Earth Orbit) only for, e.g., a 50 meter dish at l < 1cm., and therefore offers no significant advantage over SAR processing with a standard antenna.

Coherent Polarization Diversity.

It is shown in Reference [5] that coherent processing of a polarization-diverse signal backscattered from ice exhibits a characteristic probability density function for HH - VV phase shift that is strongly peaked over a +1 to -1 radian width (see Figure 6). Since sea clutter probability density is more or less uniformly distributed with respect to this parameter, ice discrimination on this basis is possible. No commercially available system currently employs this technology. Modification of any system that employs two coherent phased arrays, as for interferometry, might be easily done to incorporate discrimination on this basis. Such systems are, however, also typically capable of altitude measurement of sufficient precision to make high-confidence berg identification possible.

Stepped Frequency, Burst-to-Burst Agile SAR.

All of the SAR radars discussed herein achieve range resolution with chirp waveforms. A stepped frequency radar design, employing bursts of n (= 2^p) discrete stepped frequency pulses is an alternative requiring a frequency synthesizer that can be switched rapidly from frequency to frequency while maintaining phase coherence. Such devices are available , and permit, moreover, burst-to-burst frequency agility, which would provide an independent sample with every burst. Incoherent processing of such a signal would reduce the standard deviation of both sea and ice signals to reproduce approximately the ratios of Figures 2 and 3 with both ice and clutter signals nearly constant (variation about 10dB down) from original Rayleigh, providing excellent clutter rejection at large angles of incidence, as in the assumed drone configuration.

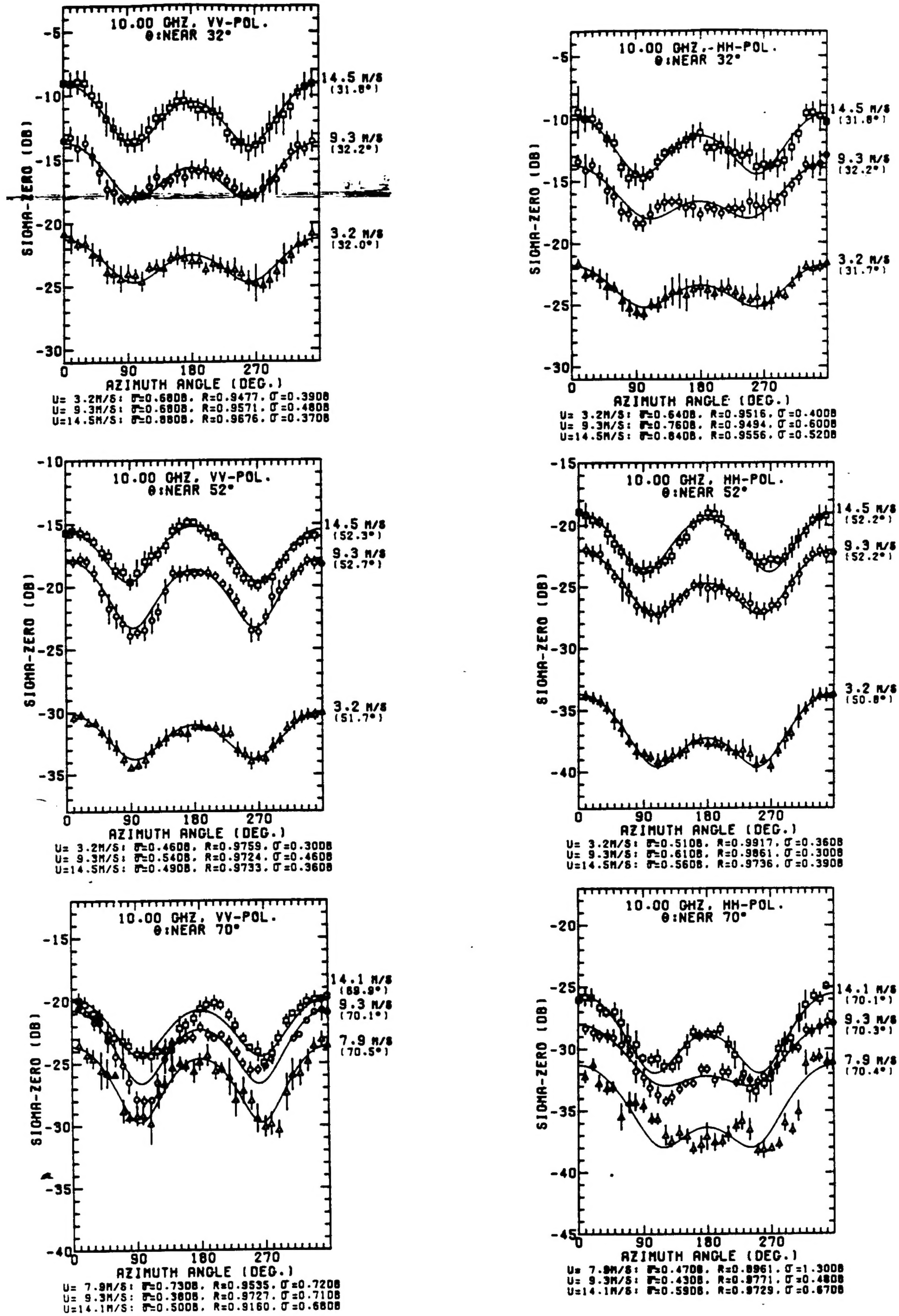


Figure 6. Sea Clutter Backscatter as Function of Polarization at X-band (Fung, 1994).

This technology requires a high PRF, which restricts the maximum unambiguous range swath to a few tens of kilometers. The cross-range ambiguity length per look is reduced by a factor of 1/n, but readily accommodates multiple look high resolution airborne modes of operation (but not satellite, for which this parameter is reduced by the ratio of aircraft to satellite velocities). It is not apparent that such a system is currently available.

Non-Radar Systems.

EO/IR Operation.

Airborne search with non-radar sensors within controlled airspace (above 6000 ft.) is rarely possible at latitudes of interest to the IIP for much of the year. Available drones, including UAV and commercial options, may achieve required visibility for effective search with EO or IR sensors by operating at altitudes below the visual ceiling by encroaching into uncontrolled airspace without safety implications for IIP personnel. Advantages of attempted operation in one of these modes as opposed to the previously described small-cell synthetic aperture mode are probably non-existent, since only intermittent operation is likely to be possible. The MAE UAV is available with a compatible alternate sensor package incorporating these sensors. Safety of other uncontrolled airspace users are probably not significantly affected by IIP choice of this operational mode. Insurance/survivability implications for drones in this mode may be important, and have not been estimated.

Transponders.

Actively emitting transponders, deposited on large bergs, have been previously tested by the IIP and found not cost effective. A principle problem encountered is that iceberg calving may result in loss of transponder, or association of the transponder with an insignificant fraction of the originally tagged mass. Solutions to this problem involving very inexpensive beacon-type transponders transmitting on a schedule maintained by digital clocks, and tracked by off-the shelf time-of-arrival (TOA) sensors have some attractiveness as an alternative method of obtaining approximately the current level of operations effectiveness at reduced cost, but are not capable of achieving the higher level of effectiveness that is possible with low altitude, very frequent drone operation as described above.

SUMMARY

The following conclusions are justified on the basis of the sensor portion of the study:

- Worthwhile improvement of current IIP operations to provide greater, but difficult to quantify, reliability of LAKI determination, reduction of leakers, and more complete understanding of the effects of current errors can be achieved by automation of data collection and processing methods, but will still be limited by size estimation and drift model inadequacies.

- Anticipated RADARSAT and Cape Race Groundwave Radar data is not expected to obviate the necessity of airborne search for LAKI determination, but is available for purchase, and could provide substantial reduction of risk associated with limiting search to a narrower region around the LAKI.

- Upgrade of sensors to airborne SAR (STAR1, STAR2 as examples) could achieve high reliability detection, for bergs large enough to occupy at least 4 pixels for sea states corresponding to winds less than about 14.5 m/sec, but only at a false alarm rate of about 5% for these systems, which are not necessarily optimized for ice discrimination, employing incidence angles as low as eight degrees. Number of sorties per two week interval could be reduced to two, with improved coverage. Either of these systems assume utilization of platform operation at about 400 knots speed for maximum efficiency.

- The false alarm rate could be significantly reduced for airborne SARs by providing for automated grey scale thresholding with a threshold varying as a function of incidence angle to optimally discriminate ice from clutter, and avoiding near vertical incidence.

- Drone (MAE UAV or commercial) operations offer economic operation at high revisit rates, but are capital cost intensive and may have unavoidable high labor costs because of pilot union assessment of labor hours to unpiloted vehicles. False alarm considerations are same as for other airborne radars.

- If union labor restrictions can be avoided, drone utilization can offer a combination of low operating cost and high resolution, permitting growlers as small as 8m to be detected at high reliability and low false alarm rate. Note that there are no inherent sensor advantages to drone vs. STAR1 or STAR2 operations.

- Changes to burst-to-burst agile stepped frequency SAR with incoherent processing would provide another quantum improvement in false alarm rate, if swaths avoided low incidence angle (near-vertical) looks.

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